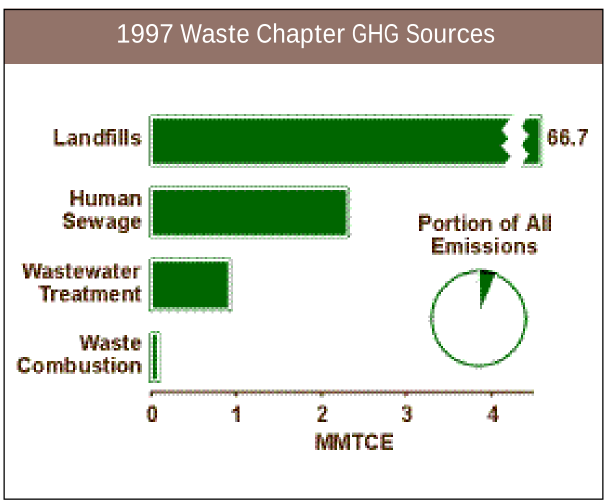
7. Waste

Certain waste management and treatment activities are sources of greenhouse gas emissions. Particularly the anaerobic decomposition of organic wastes by bacteria can result in the generation of methane (CH_4). Currently, anaerobic decomposition processes in landfills are estimated to be the largest anthropogenic source of methane emissions in the United States, accounting for 37 percent (see Figure 7-1). Smaller amounts of methane are emitted from wastewater systems by bacteria used in various treatment processes. Wastewater treatment systems are also a potentially significant source of nitrous oxide (N_2O) emissions; however, methodologies are not currently available to develop a complete estimate. Emissions from the treatment of the human sewage component of wastewater were estimated, however, using a simplified methodology. Waste combustion, both in incinerators and through open burning, were also a small source of N_2O. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) are emitted by each of these sources, but are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste sector is presented in Table 7-1 and Table 7-2.

Overall, in 1997, waste activities generated emissions of 70.0 MMTCE, or 3.9 percent of total U.S. greenhouse gas emissions.

Figure 7-1



Landfills

Landfills are the largest anthropogenic source of methane (CH_4) emissions in the United States. In 1997, emissions were approximately 66.7 MMTCE (11.6 Tg). Emissions from municipal solid waste (MSW) landfills, which received about 61 percent of the total solid waste generated in the United States, accounted for about 93 percent of total landfill emissions, while industrial landfills accounted for the remainder. There were over 2,500 landfills in the U.S. (BioCycle 1998), with the largest landfills having received most of the waste and having generated the majority of emissions.

Methane emissions result from the decomposition of organic landfill materials such as yard waste, household garbage, food waste, and paper. This decomposition process is a natural mechanism through which microorganisms derive energy. After being placed in a landfill, organic waste first decomposes aerobically (in the presence of oxygen) and is then attacked by anaerobic bacteria, which convert organic matter to substances such as cellulose, amino acids, and sugars. These simple substances are further broken

Table 7-1: Emissions from Waste (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997
CH_4	**57.1**	**58.4**	**58.7**	**60.6**	**62.5**	**64.5**	**66.0**	**67.6**
Landfills	56.2	57.6	57.8	59.7	61.6	63.6	65.1	66.7
Wastewater Treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
N_2O	**2.1**	**2.2**	**2.2**	**2.3**	**2.3**	**2.3**	**2.4**	**2.4**
Human Sewage	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.3
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**59.2**	**60.6**	**60.9**	**62.8**	**64.8**	**66.9**	**68.4**	**70.0**

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (Tg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997
CH_4	**10.0**	**10.2**	**10.3**	**10.6**	**10.9**	**11.3**	**11.5**	**11.8**
Landfills	9.8	10.0	10.1	10.4	10.8	11.1	11.4	11.6
Wastewater Treatment	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_2O	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Human Sewage	+	+	+	+	+	+	+	+
Waste Combustion	+	+	+	+	+	+	+	+

+ Does not exceed 0.05 Tg
Note: Totals may not sum due to independent rounding.

down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. Methane producing anaerobic bacteria then convert these fermentation products into stabilized organic materials and a biogas consisting of approximately 50 percent carbon dioxide and 50 percent methane by volume. In general, the CO_2 emitted is of biogenic origin and primarily results from the decomposition—either aerobic or anaerobic—of organic matter such as food or yard wastes.[1] The percentage of carbon dioxide in the biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen 1987). Methane production typically begins one or two years after waste placement in a landfill and may last from 10 to 60 years.

Between 1990 and 1997, estimates of methane emissions from landfills have increased slightly (see Table 7-3 and Table 7-4). The relatively constant emissions estimates are a result of two counter-acting trends: (1) the amount of MSW in landfills contributing to methane emissions has increased (thereby increasing the potential for emissions), and (2) the amount of landfill gas collected and combusted by landfill operators has also increased (thereby reducing emissions).

Methane emissions from landfills are a function of several factors, including: the total amount of MSW landfilled over the last 30 years, which is related to total MSW landfilled per year; composition of the waste in place; the amount of methane that is recovered and either flared or used for energy purposes; and the amount of methane oxidized in landfills before being released into the atmosphere. The estimated total quantity of waste in place contributing to emissions increased from about 4,926 teragrams in 1990 to 5,791 teragrams in 1997, an increase of 18 percent (see Annex I). During this same period, the estimated methane recovered and flared from landfills increased as well. In 1990, for example, approximately 1.5 teragrams (Tg) of methane were recovered and combusted (i.e., used for energy or flared) from landfills. In 1992, the estimated quantity of methane recovered and combusted increased to 1.8 Tg.[2]

[1] Emissions and sinks of biogenic carbon are accounted for in the Land-Use Change and Forestry chapter.

[2] The EPA is presently reviewing new data on landfill gas recovery and flaring. It is anticipated that the national total for methane recovery and flaring will be significantly larger based on this new information.

Table 7-3: CH_4 Emissions from Landfills (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996	1997
MSW Landfills	60.6	61.9	63.8	65.5	67.3	69.2	70.6	72.0
Industrial Landfills	4.2	4.3	4.4	4.5	4.6	4.8	4.9	5.0
Recovered	(8.6)	(8.6)	(10.3)	(10.3)	(10.3)	(10.3)	(10.3)	(10.3)
Net Emissions	**56.2**	**57.6**	**57.8**	**59.7**	**61.6**	**63.6**	**65.1**	**66.7**

Note: Totals may not sum due to independent rounding.

Table 7-4: CH_4 Emissions from Landfills (Tg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997
MSW Landfills	10.6	10.8	11.1	11.4	11.7	12.1	12.3	12.6
Industrial Landfills	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.9
Recovered	(1.5)	(1.5)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)
Net Emissions	**9.8**	**10.0**	**10.1**	**10.4**	**10.8**	**11.1**	**11.4**	**11.6**

Note: Totals may not sum due to independent rounding.

Over the next several years, the total amount of MSW generated is expected to continue increasing. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In addition, the quantity of methane that is recovered and either flared or used for energy purposes is expected to increase, partially as a result of a new regulation that will require large landfills to collect and combust landfill gas.

Methodology

Based on the available information, methane emissions from landfills were estimated to equal methane production from municipal landfills, plus methane produced by industrial landfills, minus methane recovered and combusted, and minus the methane oxidized before being released into the atmosphere.

The methodology for estimating CH_4 emissions from municipal landfills is based on an updated model that tracks changes in the population of landfills in the United States over time. This model is based on the pattern of actual waste disposal by each individual landfill surveyed by the EPA's Office of Solid Waste in 1987. A second model was employed to estimate emissions from the landfill population data (EPA 1993). For each landfill in the data set, the amount of waste in place contributing to methane generation was estimated using its year of opening, its waste acceptance rate, and total waste disposed in landfills. Data on national waste disposed in landfills each year was apportioned by landfill. Emissions from municipal landfills were then estimated by multiplying the quantity of waste contributing to emissions by emission factors (EPA 1993). For further information see Annex I.

To estimate landfill gas recovered per year, data on current and planned landfill gas recovery projects in the United States were obtained from Governmental Advisory Associates (GAA 1994). The GAA report, considered to be the most comprehensive source of information on gas recovery in the United States, has estimates for gas recovery in 1990 and 1992. In addition, a number of landfills were believed to recover and flare methane without energy recovery and were not included in the GAA database. To account for the amount of methane flared without energy recovery, the estimate of gas recovered was increased by 25 percent (EPA 1993).

The amount of methane oxidized was assumed to be 10 percent of the methane generated. Methane recovered and oxidized was subtracted from the methane generated from municipal and industrial landfills to arrive at net methane emissions. Emissions from industrial sites were assumed to be seven percent of total emissions from municipal landfills.

Data Sources

The model, including actual waste disposal data from individual landfills, was developed from a survey performed by the EPA Office of Solid Waste (EPA 1988). National landfill waste disposal data for 1988 through 1997 were obtained from *BioCycle* (1998). Documentation on the landfill methane emissions methodology employed is available in EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993). Emission factors were taken from Bingemer and Crutzen (1987) and the Governmental Advisory Associates (GAA 1994).

Uncertainty

There are several uncertainties associated with the estimates of methane emissions from landfills. The primary one concerns the characterization of landfills. There is a lack of information on the area landfilled and total waste in place (the fundamental factors that affect methane production). In addition, little information is available on the quantity of methane flared at non-energy-related projects and the number of landfill closures. Finally, the statistical model used to estimate emissions is based upon methane generation at landfills that currently have developed energy recovery projects, and may not precisely capture the relationship between emissions and various physical characteristics of individual landfills. Overall, uncertainty is estimated to be roughly ±30 percent.

Wastewater Treatment

The breakdown of organic material in wastewater treatment systems produces methane when it occurs under anaerobic conditions. During collection and treatment, wastewater may be incidentally as well as deliberately maintained under anaerobic conditions. The methane produced during deliberate anaerobic treatment is typically collected and flared or combusted for energy. However, whenever anaerobic conditions develop, some of the methane generated is incidentally released to the atmosphere. Untreated wastewater may also produce methane if held under anaerobic conditions.

Organic content, expressed in terms of biochemical oxygen demand (BOD), determines the methane producing potential of wastewater. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes. Under anaerobic conditions, however, wastewater with higher BOD concentrations will produce more methane than wastewater with lower BOD. The amount of methane produced is driven by the extent to which the organic material is broken down under anaerobic versus aerobic conditions.

In 1997, methane emissions from municipal wastewater were 0.9 MMTCE (0.2 Tg). Emissions have increased slightly since 1990 reflecting the increase in the U.S. human population. No estimates have been developed to indicate any changes in the manner in which wastewater is managed in the United States during this period. Table 7-5 provides emission estimates from domestic wastewater treatment.

At this time, data are not sufficient to estimate methane emissions from industrial wastewater sources. Further research is ongoing at the EPA to better quantify emissions from this source.

Methodology

Wastewater methane emissions are estimated using the default IPCC methodology (IPCC/UNEP/OECD/IEA 1997). The total population for each year was multiplied by a wastewater BOD production rate to determine total wastewater BOD produced. It was assumed that, per capita, 0.05 kilograms of wastewater BOD5[3] is produced per day and that 15 percent of wastewater BOD5 is anaerobically digested. This proportion of BOD was then multiplied by an emission factor of 0.22 Gg CH_4/Gg BOD5.

Data Sources

Human population data for 1990 to 1997 were supplied by the U.S. Census Bureau (1998). The emission factor employed was taken from Metcalf & Eddy (1972). Table 7-6 provides U.S. population and wastewater BOD data.

Uncertainty

Domestic wastewater emissions estimates are highly uncertain due to the lack of data on the occurrence of anaerobic conditions in treatment systems, es-

Table 7-5: CH_4 Emissions from Domestic Wastewater Treatment

Year	MMTCE	Tg
1990	0.9	0.2
1991	0.9	0.2
1992	0.9	0.2
1993	0.9	0.2
1994	0.9	0.2
1995	0.9	0.2
1996	0.9	0.2
1997	0.9	0.2

pecially incidental occurrences. It is also believed that industrial wastewater is responsible for significantly more methane emissions than domestic wastewater treatment.

Human Sewage

Human sewage is transported for treatment in the form of domestic wastewater. Nitrous oxide (N_2O) is emitted from both domestic and industrial wastewater containing nitrogen-based organic matter and is produced through natural processes known as nitrification and denitrification. Nitrification occurs aerobically and converts ammonia into nitrate, while denitrification occurs anaerobically, and converts nitrate to N_2O. It is estimated that the amount of N_2O emitted from wastewater treatment plants accounts for approximately 5 to 10 percent of annual global discharge (Spector 1997 McElroy et al. 1978). Human sewage is believed to constitute a significant portion of the material responsible for N_2O emissions from wastewater (Spector, 1997). There is insufficient information available at this time to estimate emissions from industrial wastewater and the other components of domestic wastewater. In general, N_2O generation in wastewater systems is affected by temperature, pH, biochemical oxygen demand (BOD), and nitrogen concentration. BOD is the amount of dissolved oxygen used by aerobic microorganisms to completely consume the available organic matter (Metcalf & Eddy 1972).

Table 7-6: U.S. Population (millions) and Wastewater BOD Produced (Gg)

Year	Population	BOD5*
1990	249.3	4,554
1991	252.0	4,602
1992	254.9	4,655
1993	257.7	4,706
1994	260.2	4,752
1995	262.7	4,797
1996	265.1	4,842
1997	267.6	4,887

* The 5 day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1972)

Emissions of N_2O from human sewage treated in wastewater systems was estimated to be 2.3 MMTCE (27 Gg) in 1997. An increase in the U.S. population and the per capita protein intake resulted in an overall increase of 12 percent in N_2O emissions from human sewage between 1990 and 1997 (see Table 7-7).

Table 7-7: N_2O Emissions from Human Sewage

Year	MMTCE	Gg
1990	2.1	24
1991	2.1	25
1992	2.2	26
1993	2.2	26
1994	2.3	27
1995	2.2	27
1996	2.3	27
1997	2.3	27

Methodology

Nitrous oxide emissions from human sewage were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). The equation in IPCC was modified slightly to convert N_2O-N to N_2O by using a conversion factor of the atomic weight of N_2O to that of N_2 (44/28). This is illustrated below:

$$N_2O(s) = (\text{Protein}) \times (\text{Frac}_{NPR}) \times (\text{NR People}) \times (\text{EF}) \times (^{44}/_{28})$$

where,

$N_2O(s)$ = N_2O emissions from human sewage

Protein = Annual, per capita protein consumption

Frac_{NPR} = fraction of nitrogen in protein

NR People = U.S. population

EF = Emission factor

(44/28) = The atomic weight ratio of N_2O to N_2

[3] The 5 day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1972).

Data Sources

U.S. population data were taken from the U.S. Census Bureau (1998). Data on the annual per capita protein consumption were provided by the United Nations Food and Agriculture Organization (FAO 1998) (see Table 7-8). Because data on protein intake were unavailable for 1997, the average value of per capita protein consumption over the years 1990 through 1996 was used. An emission factor has not been specifically estimated for the United States. As a result, the default IPCC value (0.01 kg N_2O-N/kg sewage-N produced) was applied. Similarly, the fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

Table 7-8: U.S. Population (millions) and Average Protein Intake (kg/person/year)

Year	Population	Protein
1990	249.3	38.9
1991	252.0	39.6
1992	254.9	39.8
1993	257.7	39.9
1994	260.2	40.6
1995	262.7	40.3
1996	265.1	40.7
1997	267.6	40.0

Uncertainty

The U.S. population (NR people) and per capita protein intake data (Protein) are believed to be fairly accurate. There is significant uncertainty, however, in the emission factor (EF) employed due to regional differences that would likely affect N_2O emissions but are not accounted for in the default IPCC factor. In contrast, the fraction of nitrogen in protein ($Frac_{NPR}$) is believed to be quite accurate. Despite the increase in N_2O emissions from 1990 through 1997, these estimates from human sewage are significantly lower than other more recent estimates (Spector 1997) of total N_2O emissions from both domestic and industrial wastewater treatment. EPA is currently supporting further research to develop a comprehensive estimate of emissions from this source.

Waste Combustion

Waste combustion involves the burning of garbage and non-hazardous solids, called municipal solid waste (MSW), and has been identified as a source of nitrous oxide (N_2O) emissions.[4] In 1992, there were over 160 municipal waste combustion plants in the United States (EPA 1997b). Emissions from this source are dependent on the types of waste burned and combustion temperatures (De Soete 1993). Nitrous oxide emissions from MSW combustion were estimated to be 0.1 MMTCE (1 Gg) in 1997, and have fluctuated only slightly since 1990 (see Table 7-9).

Table 7-9: N_2O Emissions from Waste Combustion

Year	MMTCE	Gg
1990	0.1	1
1991	0.1	1
1992	0.1	1
1993	0.1	1
1994	0.1	1
1995	0.1	1
1996	0.1	1
1997	0.1	1

Methodology

Estimates of nitrous oxide emissions from MSW combustion in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emission Factors (EPA 1997a). According to this methodology, emissions of N_2O from MSW combustion is the product of the mass of MSW (metric ton MSW) combusted, the emission factor of N_2O emitted per unit mass of waste combusted (g N_2O/metric ton), and an N_2O emissions control removal efficiency. For MSW combustion in the United States, an emission factor of 30 g N_2O/metric ton MSW, and an estimated emissions control removal efficiency of zero percent were used.

Data Sources

Data on the quantity of MSW generated and combusted was taken from the April 1998 issue of *BioCycle* (Glenn 1998). Table 7-10 provides MSW generation and

[4] Emissions of CO_2 from the combustion of petroleum-based plastics are accounted for under CO_2 from Fossil Fuel Combustion as a non-energy use of petroleum.

percentage combustion data. The emission factor of N_2O emissions per quantity of MSW combusted was taken from Olivier (1993).

Table 7-10: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted

Year	Waste Generation	Combusted (%)
1990	266,541,881	11.5
1991	254,796,765	10.0
1992	264,843,388	11.0
1993	278,572,955	10.0
1994	293,109,556	10.0
1995	296,586,430	10.0
1996	297,268,188	10.0
1997	309,075,035	9.0

Uncertainty

As with other combustion-related sources of nitrous oxide, emissions are affected by combustion conditions (De Soete, 1993). In part, because insufficient data exists to provide detailed estimates of N_2O emissions for individual combustion facilities, the estimates presented are highly uncertain. The emission factor for N_2O from MSW combustion facilities used in the analysis is a default used to estimate N_2O emissions from facilities worldwide (Olivier, 1993). As such, it has a range of uncertainty of an order of magnitude (between 25 and 293 g N_2O/metric ton MSW combusted) (Watanabe, et al. 1992). Due to a lack of relevant information on the control of N_2O emissions from MSW combustion facilities in the U.S., the estimate of zero percent for N_2O emissions control removal efficiency is also uncertain. MSW combustion activity data used in this analysis, as published in *BioCycle* (1998), were compared with data published by the EPA's Office of Solid Waste (EPA 1997b) and were found to be relatively consistent (see Table 7-11).

Table 7-11: U.S. Municipal Solid Waste Combusted by Data Source (Metric Tons)

Year	BioCycle	EPA
1990	30,652,316	28,958,820
1991	25,479,677	30,256,974
1992	29,132,773	29,675,982
1993	27,857,295	29,884,776
1994	29,310,956	29,494,422
1995	29,658,643	30,384,066
1996	29,726,819	NA
1997	30,641,940	NA

NA (Not Available)

Waste Sources of Criteria Pollutants

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of criteria air pollutant emissions. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs) from waste sources for the years 1990 through 1997 are provided in Table 7-12.

Methodology and Data Sources

These emission estimates were taken directly from the EPA's *Draft National Air Pollutant Emissions Trends, 1900-1997* (EPA 1998). This EPA report provides emission estimates of these gases by sector, using a "top down" estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA data bases.

Uncertainty

Uncertainties in these estimates are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.

Table 7-12: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997
NO_x	**83**	**86**	**87**	**112**	**103**	**89**	**91**	**94**
Landfills	+	+	+	1	1	1	1	1
Wastewater Treatment	+	+	+	+	+	+	+	+
Waste Combustion[a]	82	85	86	107	99	88	89	93
Miscellaneous[b]	+	1	1	4	3	1	1	1
CO	**979**	**1012**	**1032**	**1133**	**1111**	**1075**	**1091**	**1126**
Landfills	1	1	2	2	2	2	2	2
Wastewater Treatment	+	+	+	+	+	+	+	+
Waste Combustion[a]	978	1,011	1,030	1,130	1,108	1,073	1,089	1,124
Miscellaneous[b]	+	+	+	1	1	1	1	+
NMVOCs	**895**	**907**	**916**	**949**	**949**	**968**	**393**	**408**
Landfills	58	60	63	67	73	68	20	21
Wastewater Treatment	57	58	61	63	64	61	58	62
Waste Combustion[a]	222	227	230	256	248	237	240	246
Miscellaneous[b]	558	562	563	563	564	602	75	79

[a] Includes waste incineration and open burning (EPA 1998)

[b] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 Gg